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Residential Retrofitting: Integrated Building Performance Evaluation

Key words: Energy assessment, carbon footprint, thermal comfort, Indoor air quality, Natural gas boiler, Air Source Heat Pump

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This study evaluates energy consumption, carbon emissions, and thermal comfort of a residential dwelling subject to energy retrofit measures.

Introduction

Globally, the urgency to reduce carbon emissions has increased significantly to foster an environmentally sustainable future. Existing residential buildings alone account for approximately 17% of these emissions, representing about 25% of total energy consumption [1]. Reports indicate that over 97% of existing buildings in the EU require renovation, highlighting the Renovation Wave strategy as a central pillar of the European Green Deal [2], [3], [4]. A core element of retrofitting strategies is replacing traditional, fossil-fuel-based heating systems with electrified solutions, such as heat pumps. This research examines the carbon footprint associated with residential heating by comparing pre- and post-retrofit scenarios, with a specific focus on the impact of heat pump electrification on carbon emissions. This study evaluates energy consumption and carbon emissions pre- and post-retrofit of a semi-detached house located in Dublin, Ireland. In addition, it assesses thermal comfort using the Predictive Mean Vote (PMV) index to evaluate improvements resulting from enhanced building envelope and heating system upgrades.

Methodology

The methodology utilized in this study involves analysing utility energy data from pre- and post-retrofitted buildings, along with real-time monitoring of post-retrofitting for thermal comfort analysis, as shown in **Figure 1**.

Case Background

For the current case study residential building, based on data for generalized U-values, the assumed U-values ($W·m^{-2}·K^{-1}$) for pre and post-retrofit of the building components are presented in **Table 1** [5]. Furthermore, the floor area of the dwelling in its pre-retrofit state is 170 m^2, and the number of occupants is 2. In the post-retrofit state, the area increased to 189 m^2 due to the conversion of a garage space into dwelling space, and the number of occupants also increased to 3. Along with improved insulation and energy efficiency, the retrofit also included an air source heat pump (ASHP). The heating system was upgraded from a natural gas boiler (NGB) with an efficiency of 90% (as specified by the manufacturer) to a 12 kW ASHP with a coefficient of performance (COP) of 3.42 (as specified by the manufacturer).

Measurement and Monitoring

For this analysis, utility billing data were systematically collected from the pre-retrofit and post-retrofit phases of the dwelling. To provide more granular consumption insights, sub-monitoring systems were also installed in post-retrofitting to isolate the energy consumption of critical components, including the ASHP, with a time frequency of 1 minute. Furthermore, a carbon emissions analysis is conducted between the pre- and post-retrofit scenarios, based on energy consumption data. For thermal comfort, sensor-based monitoring was conducted in the living room of the selected house, with sensors measuring temperature, relative humidity, and carbon component levels at an hourly time frequency after retrofit. Several thermal comfort models are available, accounting for environmental, cultural, lifestyle, and age-related differences [6]. Fanger's model is the most commonly applied thermal comfort model for indoor conditions, which forms the basis for several international standards, including ISO 7730, ASHRAE, and the Chinese standard GB/18049 [7]. The PMV index based on Fanger's model is utilized in this study. In practice, the PMV equation is often applied through dedicated software; this study implements it via a Python script [8]. Required inputs include the monitored indoor parameters, temperature and humidity, metabolic rate (considered 1.1), a clothing insulation level of 0.67, and an air velocity of 0.2 m/s, considering living-room conditions with mechanical ventilation. These parameters align with ASHRAE 55 standards [9].

Table 1. *Pre and Post retrofit U-values.*

Component (pre-retrofit)	U-Value ($W·m^{-2}·K^{-1}$)	Component (post-retrofit)	U-value ($W·m^{-2}·K^{-1}$)
Roof	2.3	Roof	0.16
Wall	2.1	Wall	0.2
Floor	1.2	Floor	0.18
Window	3.5	Window	1.6
Door	2.8	Door	1.4

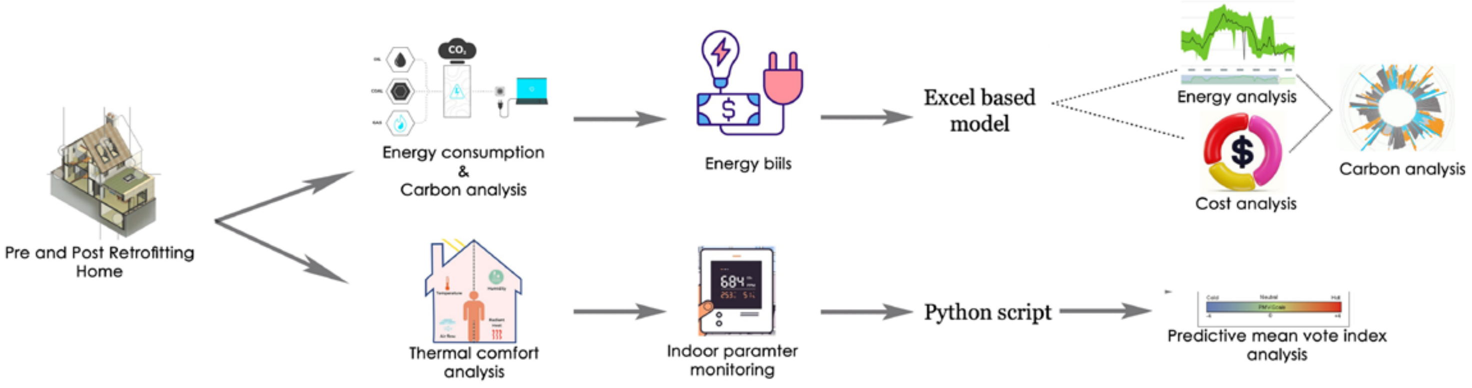

Figure 1. Methodology adaptation.

Analysis And Discussion

Energy saving performance

Figure 2 presents the energy performance for the pre- and post-retrofit scenarios. These results are based on one of metered electricity and gas consumption data, along with utility bills. Based on Primary Energy (PE) consumption, the pre- and post-retrofit annual consumption (normalized with respect to pre- and post- floor area) are 83.8 kWh·m^{-2} and 44.5 kWh·m^{-2}, respectively. In the case of post-retrofit, approximately 80% of PE consumption is due to space and water heating, of which DHW accounts for approximately 63% or 22.4 kWh·m^{-2}, space heating accounts for 13.2 kWh·m^{-2} and 8.9 kWh·m^{-2} accounts for other activities.

Carbon footprint

Based on energy use and carbon coefficients, **Figure 3** compares the carbon footprints before and after retrofit. Post-retrofit annual operational emissions are 6.4 kgCO$_2$eq·m^{-2}, representing a 60% reduction from the pre-retrofit value of 15.9 kgCO$_2$eq·m^{-2}. In the post-retrofit breakdown, DHW is highest at 3.1 kgCO$_2$eq·m^{-2}, followed by space heating (2.1) and other uses (1.2). Pre-retrofit, gas contributed 11.2 and electricity 4.7 kgCO$_2$eq·m^{-2}. Compared to the average annual carbon footprint of an Irish dwelling of 4.6 tCO$_2$/year [10], the post-retrofit footprint is ~75% lower. This suggests the retrofitted house performs significantly better than average residential building stock. However, further analysis is needed to assess whole-life carbon performance, especially embodied impacts. While operational emissions are often targeted through heating upgrades and electricity decarbonization, embodied carbon is increasingly critical, projected to exceed operational emissions in new build constructions by 2030, accounting for ~60% of residential sector emissions [11].

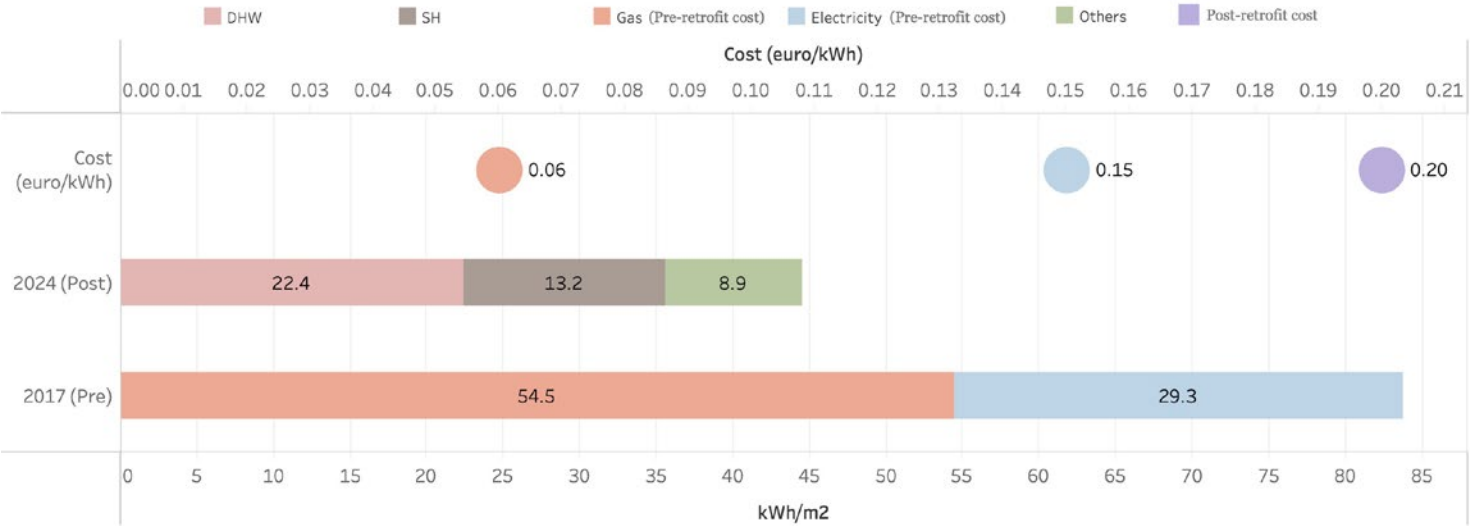

Figure 2. Primary energy performance.

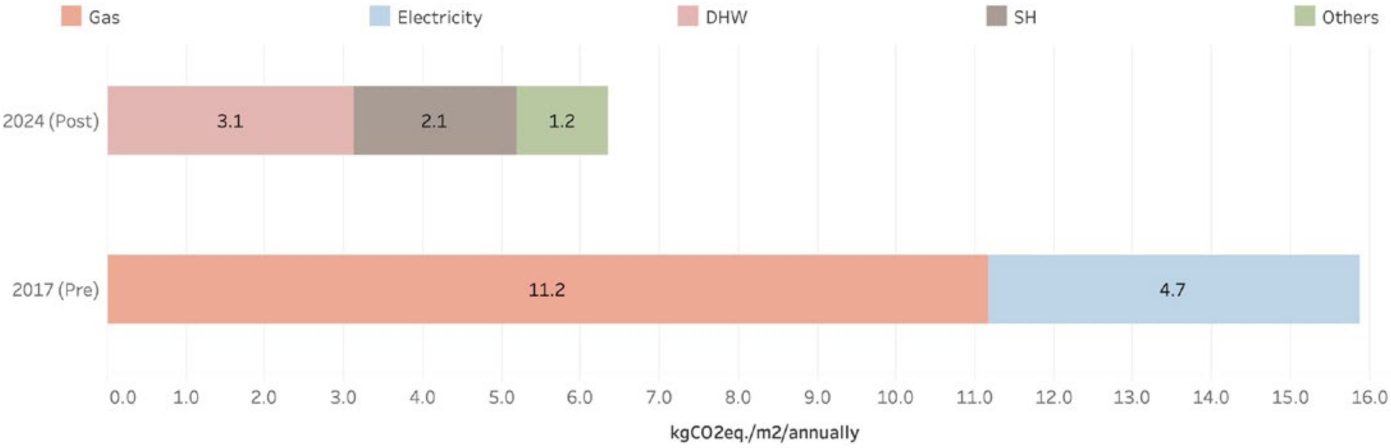

Figure 3. Carbon footprint analysis.

Thermal comfort analysis

For thermal comfort assessment, sensors were installed in the living room of the selected house to track both relative humidity and indoor temperature. **Figure 4** displays the PMV and indoor CO_2 levels; the PMV reflects thermal comfort, while the CO_2 levels indicate air quality and occupancy patterns. The green-shaded zone represents the acceptable PMV comfort band (–0.5 to +0.5), along with the acceptable range for indoor CO_2 levels [9]. Indoor CO_2 levels mostly remain below 500 ppm, suggesting adequate ventilation and moderate occupancy throughout the year. The PPD (Predicted Percentage of Dissatisfied) is around 25%, which is calculated utilizing the PMV results and corresponds to PMV values around ±0.5. It is observed that PMV values dropped significantly below -1 during late autumn and early winter, indicating a shift toward thermal discomfort. This suggests inadequate heating or slow diurnal heating response as the external temperatures drop. Furthermore, in addition to this seasonal variation, there is an automated window that operates based on indoor CO_2 concentration, which also aligns with the finding of acceptable CO_2 readings and may be the cause of the varied PMV range during the cooler months. In summary, the system may benefit from more dynamic heating control or adaptive setpoints during shoulder seasons, even when ventilation appears sufficient. These results underline the need for integrated thermal and air quality strategies to maintain year-round comfort.

Conclusion

This study investigates the impact of retrofitting on energy consumption, carbon footprint, and thermal comfort. The analysis evaluates energy consumption data and utility bills, allowing for a thorough assessment of energy use and its associated operational carbon emissions. Based on Primary Energy (PE) annual consumption from pre-retrofit (83.8 $kWh \cdot m^{-2}$), there is an improvement of approximately 40% compared to post-retrofit PE consumption (49.5 $kWh \cdot m^{-2}$). Before the retrofit, approximately 65% of the energy was from gas, while the remaining 35% was from electricity. When evaluating carbon emissions, the post-retrofit scenario shows a notable decrease of around 60% in operational carbon footprint compared to the pre-retrofit scenario, which is approximately 6.4 kg $CO_2eq \cdot m^{-2}$ and 15.9 kg

Figure 4. PMV analysis.

$CO_2eq \cdot m^{-2}$. In pre-retrofit homes, the majority of emissions stemmed from gas consumption related to heating, whereas in the post-scenario, heating is done by an ASHP, which operates on electricity. Although the analysis shows a positive impact, as the study covers only the operational aspect of carbon footprint, further analysis from the whole-carbon perspective, encompassing the embodied aspect, is also required. Based on the initial analysis, thermal comfort was assessed using the Predicted Mean Vote (PMV) index, which ranged between 0 and -1.5 in the post-retrofit scenario, along with a Predicted Percentage of Dissatisfaction (PPD) of approximately 25%, which is based on the PMV. According to ASHRAE & ISO guidelines, an ideal PMV range is between -0.5 and +0.5; however, except for the summer period, the PMV is not in the ideal range, which is partly because of the presence of the automated window that operates based on the level in carbon concentration, which affects the indoor humidity level, partly from inadequate heating and partly from inefficient use of mechanical ventilation and heat recovery. Maintaining the balance between thermal comfort and carbon concentration is an important aspect that needs further assessment. Overall, these findings demonstrate the preliminary benefits of residential retrofits in reducing energy consumption, decreasing carbon footprint, and maintaining thermal and carbon levels from a broader perspective.

Acknowledgments

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